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Modulated photonic-crystal structures as broadband back reflectors in thin-film solar cells

J. Krc,[1] M. Zeman,[2] S. L. Luxembourg,[2] and M. Topic[1,a)]
[1]*Faculty of Electrical Engineering, University of Ljubljana, Trzaska 25, Si-1000 Ljubljana, Slovenia*
[2]*DIMES, Delft University of Technology, P.O. Box 5053, 2600 GB Delft, The Netherlands*

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A concept of a modulated one-dimensional photonic-crystal (PC) structure is introduced as a back reflector for thin-film solar cells. The structure comprises two PC parts, each consisting of layers of different thicknesses. Using layers of amorphous silicon and amorphous silicon nitride a reflectance close to 100% is achieved over a broad wavelength region (700–1300 nm). Based on this concept, a back reflector was designed for thin-film microcrystalline silicon solar cells, using *n*-doped amorphous silicon and ZnO:Al. Simulations show that the short-circuit current of the cell with a modulated PC back reflector closely resembles that of a cell with an ideal reflector. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3109781]

Advanced concepts of light management in thin-film solar cells are needed to increase the conversion efficiency and/or to reduce the thickness of the layers in the cells. Photonic crystals (PCs) have been suggested as promising candidates for improving the optical performance of solar cells.[1–7] While two- or three-dimensional PCs exhibit a high potential for efficient light scattering,[1,5] one-dimensional (1D) PCs can be used as distributed Bragg reflectors with high optical reflectance (close to 100%).[2,7] A regular 1D PC is a periodiclike multilayer structure consisting of two alternating layers each with a different refractive index (n_1, n_2) and thickness [d_1, d_2; see inset in Fig. 1(a)]. Given that $d_1 \approx \lambda_0/4n_1$ and $d_2 \approx \lambda_0/4n_2$ (λ_0—central light wavelength) for a distributed Bragg reflector, one can analytically calculate the reflectance R of a regular PC, using the following:

$$R = \left[\frac{n_1^{2m} - n_2^{2m}}{n_1^{2m} + n_2^{2m}}\right]^2, \qquad (1)$$

where m is the number of alternating-layer pairs (periods) in the PC structure and n_1 and n_2 are their refractive indices.[1] The high reflectance that can be achieved if the number of periods and the ratio between n_1 and n_2 are sufficiently large refers to a limited wavelength interval around λ_0. When applying PC structures as back reflectors (BRs) in thin-film silicon solar cells, it is required that this wavelength interval is very broad because it is only in this way that the entire light spectrum reaching the BR can be efficiently reflected back into the cell.

In this letter we introduce a concept of PCs, which we call modulated PCs, in solar cell applications for extending the interval of high reflectance over a much broader wavelength region than that obtained using a regular PC. In general, we apply the term "modulated PC" to PC structures, where either the thicknesses or the optical properties of the layers are adjusted (modulated) across the structure to achieve the desired wavelength-selective reflectance or transmittance of the PC structure.

We propose a simple modulated PC for extending the region of high reflectance by altering the layer thicknesses (period) in the PC structure. The resulting modulated structure becomes a combination of two (regular) PC parts in our case—one (light entrance side) with smaller layer thicknesses and the other with larger thicknesses [see inset in Fig. 1(c)]. The first part should assure the high reflectance of

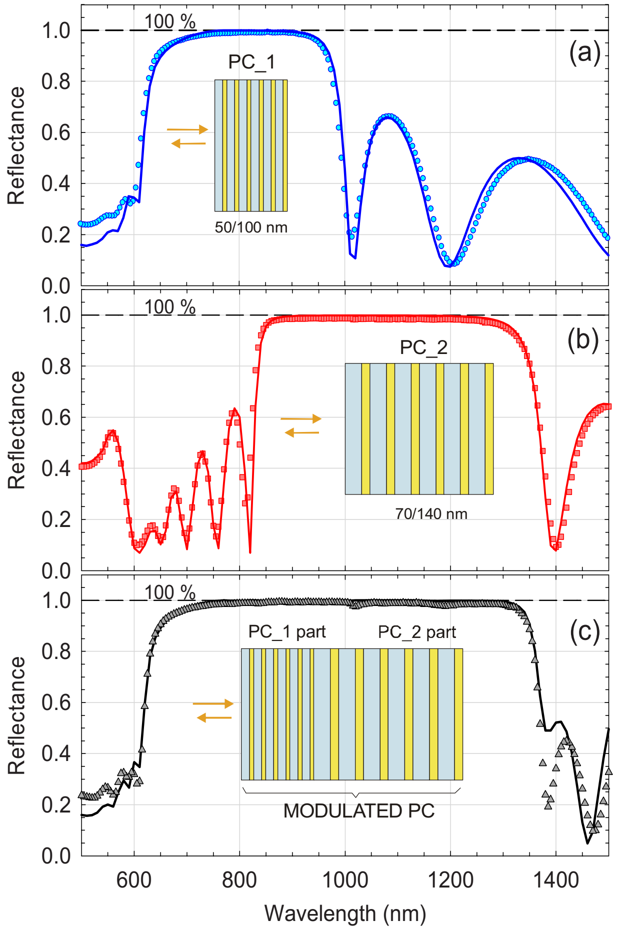

FIG. 1. (Color online) Reflectance of PC structures (symbols - measured, lines - simulated) based on a-Si:H and a-SiN$_x$:H layers deposited on a glass substrate. (a) PC_1, (b) PC_2, and (c) modulated PC made of PC_1 and PC_2. The schematics of the PC structures, thicknesses of the layers $d_{a\text{-Si:H}}/d_{a\text{-SiN}_x\text{:H}}$, are given in the insets.

[a)] Electronic mail: marko.topic@fe.uni-lj.si.

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short-wavelengths of light, while the second part should exhibit a high reflectance for longer wavelengths, thereby achieving a broadband reflectance.

The PC structures were designed and optimized using the 1D semicoherent optical simulator SUNSHINE.[8] In simulations, both wavelength dependent refractive indices and the absorption coefficients of the actual layers were taken into consideration. The same simulator was then used to predict the characteristics of a microcrystalline silicon (μc-Si:H) solar cell with the modulated PC BR.

The test PC structures were fabricated using nonconductive layers made from thin-film silicon technology: intrinsic a-Si:H and a-SiN$_x$:H films. The films were deposited by plasma enhanced chemical vapor deposition, which allows the fabrication of a-Si:H/a-SiN$_x$:H stacks in a continuous deposition run. The refractive indices of the layers were $n_{a\text{-Si:H}}=3.83$ and $n_{a\text{-SiN}_x}=1.81$ (at $\lambda=800$ nm). The PC structures were deposited on a glass substrate starting with the a-Si:H layer. Figures 1(a) and 1(b) show the measured and simulated reflectance R of two regular PC structures (PC_1 and PC_2), which also later represent the first and the second part of the modulated PC. Both PC_1 and PC_2 comprise of six periods (12 layers) with layer thicknesses $d_{a\text{-Si:H}}/d_{a\text{-SiN}_x\text{H}}$ of 50/100 and 70/140 nm, respectively. Such thicknesses assure a high reflectance of the shorter wavelengths (in this case $\lambda=700-950$ nm) by PC_1 and of the longer wavelengths ($\lambda=800-1300$ nm) by PC_2. Both the regular PC structures exhibit a high wavelength-selective reflectance (close to 100%). Figure 1(c) shows the reflectance of the test modulated PC structure, combining PC_1 and PC_2 (6+6 periods, 24 layers). One can observe that the two regions of high reflectance that correspond to PC_1 and PC_2 are combined into a single broad region for the modulated PC structure. Such extensive broadening cannot be achieved with a regular PC (using the same layer materials), neither by increasing the number of periods nor by selecting alternative layer thicknesses. It is the modulated concept that enables materials, which do not have a large ratio of refractive indices, to be used as broadband reflectors.

After demonstrating that the concept works, we designed a suitable modulated PC for a broadband BR for thin-film μc-Si solar cells. In this case, the reflector must also serve as a back electrical contact. Therefore, conductive layers, n-doped amorphous silicon (n-a-Si:H) and Al doped magnetron sputtered ZnO (ZnO:Al), were used. The refractive indices of these layers were $n_{n\text{-}a\text{-Si:H}}=3.32$ and $n_{\text{ZnO:Al}}=1.77$ ($\lambda=800$ nm). First, two regular PCs (PC_I and PC_II), were designed for covering short- and long-wavelength reflectance. At this stage both regular PCs consist of seven periods with thicknesses $d_{n\text{-}a\text{-Si:H}}/d_{\text{ZnO:Al}}$ of 40/80 and 60/120 nm, respectively. The effect of the BRs was investigated for the solar cell structure using the following configuration: glass substrate/ZnO:Al(700 nm)/p-μc-Si:H(10 nm)/i-μc-Si:H(2 μm)/n-a-Si:H(20 nm)/PC BR. Flat interfaces were assumed in the SunShine simulations (light scattering excluded). To demonstrate clearly the effect of the modulated PC BR and to avoid the pronounced interferences in the simulated external quantum efficiency (EQE) of the solar cell, an incoherent propagation of light inside a 2 μm thick i-μc-Si:H absorber layer was applied. Realistic complex refractive indices for all the layers were used in the simulations.[9] To evaluate the actual reflectance of the BR inside the cell's structure, we calculated the internal reflectance with respect to the absorber layer and not with respect to air. Thus, the i-μc-Si:H material was applied as the incident medium in simulations to determine the reflectance properly.

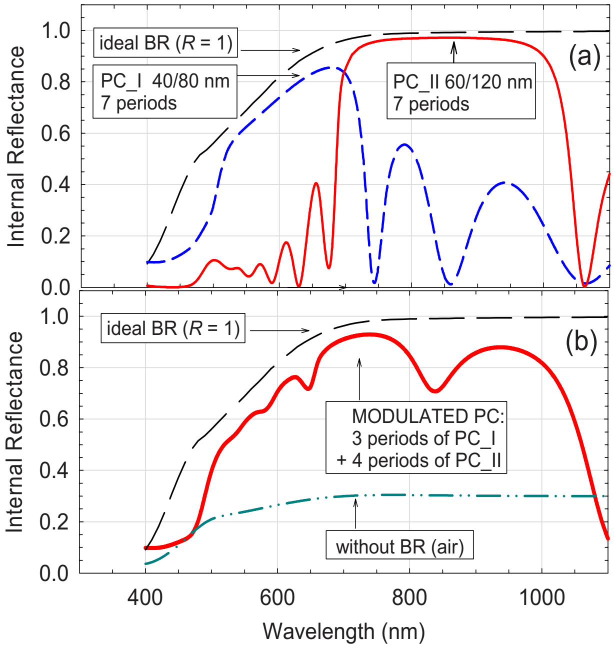

FIG. 2. (Color online) Simulated internal reflectance from the rear part of the microcrystalline silicon solar cell (n-a-Si:H/PC BR) into the i-μc-Si:H absorber layer: (a) regular PC_I and PC_II and (b) modulated PC (three periods of PC_I and four periods of PC_II). The PCs consist of conductive n-a-Si:H and ZnO:Al layers. Simulated internal reflectance of the rear structures with an ideal BR and without a BR (n-a-Si:H followed by air) are shown for comparison.

Figure 2(a) shows the internal reflectance of the PC_I and PC_II. Particularly, PC_I and PC_II were designed to provide high reflectance in the regions $\lambda=500-700$ nm and $\lambda=700-1000$ nm, respectively. We also consider the n-a-Si:H layer of the solar cell as the first layer of the PC BRs, although it was thinner (20 nm) than the optimal thicknesses of n-a-Si:H layers in the PC_I (40 nm) and PC_II (60 nm). Our simulations suggest that a thinner first n-a-Si:H layer would be advantageous since absorption losses therein are lower. Nevertheless, losses in the n-a-Si:H and ZnO:Al layers are still present, especially at $\lambda < 600$ nm, and limits the internal reflectance performance of PC_I (slopelike behavior of the R). However, the internal reflectance of the PC_II exhibits saturation at ~97%. The internal reflectance corresponding to an ideal BR (R at the rear n-a-Si:H interface of the solar cell was set to 100%) and of a cell without a BR (n-a-Si:H followed by air) are included in Fig. 2 for the sake of comparison.

For μc-Si:H solar cells, it is important that the BR has a high reflectivity over a much broader wavelength region ($\lambda \approx 500-1100$ nm), something that can be achieved neither by PC_I nor by PC_II nor by any other regular PC using the two conductive materials. To overcome this, we applied our design of a modulated PC structure based on PC_I and PC_II structures. In this design, only three periods (not seven) of PC_I and four periods of PC_II were included in the modulated PC. Thus, the total number of periods in the modulated PC remains the same (seven) as in a regular PC in order to

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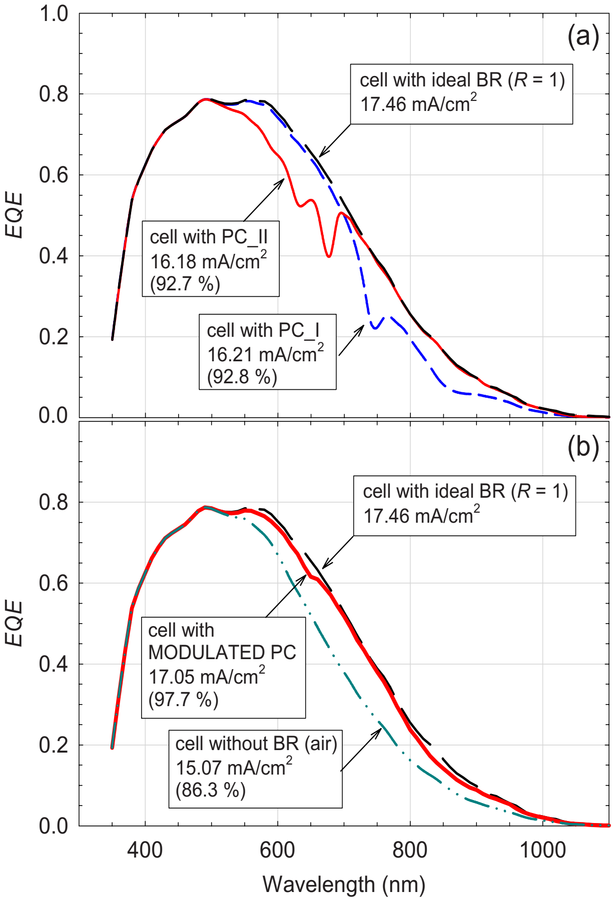

FIG. 3. (Color online) Simulated external quantum efficiency of a microcrystalline silicon solar cell (flat interfaces) with (a) regular PC_I and PC_II and (b) modulated PC BR. The corresponding short-circuit current densities are shown in the inset. The simulations for the cells with an ideal and without a BR are plotted for comparison.

justify the improvements related to the modulated PC without extending either the number of layers or deposition time. In Fig. 2(b), a high internal reflectance of the modulated PC is shown over the broad wavelength region $\lambda = 500-1000$ nm. Some interference spikes are observed at wavelengths where pronounced minima are present in the reflectance of the regular PC_I and PC_II [see Fig. 2(a)]. This is because the number of periods in the first and in the second part of the modulated PC is insufficient to compensate for the effect of deconstructive interferences, originating either from the first or second part of the PC; an almost perfect compensation was achieved for the modulated PC in Fig. 1(c).

In Fig. 3(a) the simulated EQE is plotted for the cells that have regular PC_I and PC_II BRs. To determine the EQE from optical simulations we assume an ideal extraction of charge carriers from the i-μc-Si:H absorber, which is the situation in actual state-of-the-art μc-Si:H solar cells. While the EQE of the cell with the PC_I BR is lowered in the long-wavelength region ($\lambda > 700$ nm), the cell with the PC_II exhibits reduced EQE in the middle-wavelength region ($\lambda = 500-700$ nm). The corresponding short-circuit current densities J_{SC} under reference solar irradiance AM1.5 reach 92.8% and 92.7% of the J_{SC} calculated for an ideal BR, respectively [Fig. 3(a)].

Figure 3(b) shows the results obtained from the simulated EQE of the cell with the modulated PC. In this case, the EQE over the entire wavelength region resembles closely that of a cell with an ideal BR. The observed small deviations are related to the decreases in the internal reflectance [Fig. 2(b)]. The cell with the modulated PC BR achieves 97.7% of the J_{SC} of the cell with an ideal BR; this is an additional 5% increase with respect to regular PCs. This increase in the J_{SC} leads to the same relative increase in conversion efficiency of the solar cell, given that the open-circuit voltage and the fill factor remain the same.

In summary, we propose using modulated PC structures as BRs in thin-film solar cells. The modulated PC structure exhibits a broadband high reflectance that opens up the possibility for realizing not only highly reflective but also conductive PC BRs. Using materials from thin-film silicon photovoltaic technology, the predicted EQE and J_{SC} of a microcrystalline silicon cell with a modulated PC BR resembles closely that of a cell having an ideal BR.

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